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Report developed under SBR Contract for Topic N01-037. Ship construction represents one of the more challenging planning problems in industry today. The purpose of this research is to reduce ship construction and operation costs by making optimal use of available automated fabrication facilities and designing for maintainability. An efficient algorithm for solving this class of problem has been discovered and its feasibility has been validated. A design for a commercial software product using this technology has been developed and successfully prototyped. The product would be packaged as plug-ins for commercial CAD, scheduling and ERP systems. Anticipated savings are $104 million in construction costs for U.S. shipyards over a five year period.

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Automated Planning and Design for Producability and Maintainability

Final Report – May 1 through Oct. 31, 2001

Office of Naval Research
FY 2001 Small Business Innovative Research Program
Topic Number N01-037 – Technology for Shipbuilding Affordability
Contract No. N00014-01-M-0152, Item No. 0001AD

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1. Summary

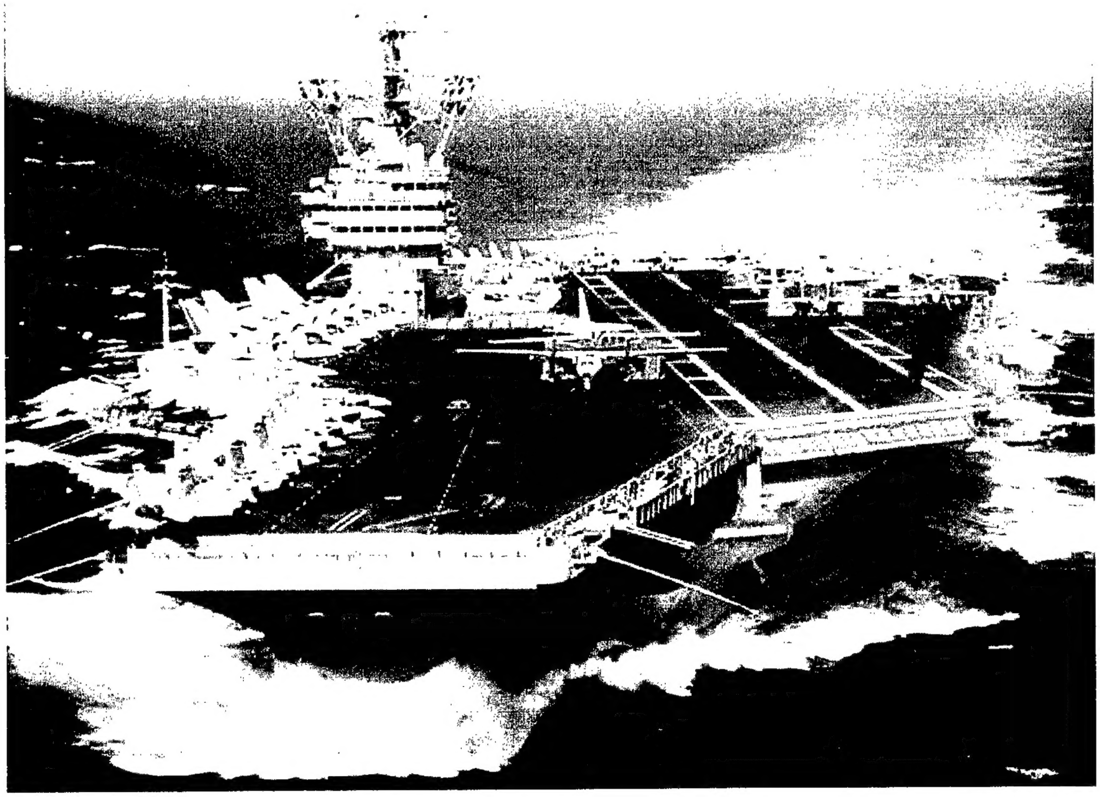
Ship construction represents one of the more challenging planning problems in industry today. The purpose of this research is to reduce ship construction and operation costs by making optimal use of available automated fabrication facilities and designing for maintainability. An efficient algorithm for solving this class of problem has been discovered and its feasibility has been validated. A design for a commercial software product using this technology has been developed and successfully prototyped. The product would be packaged as plug-ins for commercial CAD, scheduling and ERP systems. Anticipated savings are $104 million in construction costs over a five year period for U.S. shipyards.

Industrial Planning Technology Inc. is committed to developing commercial software products based on this technology and marketing to the shipbuilding, process plant, and building construction industries. The fact that Industrial Planning Technology has secured both outside equity investment and an advance purchase order for the technology is ample evidence of the commercial viability of the proposed product.

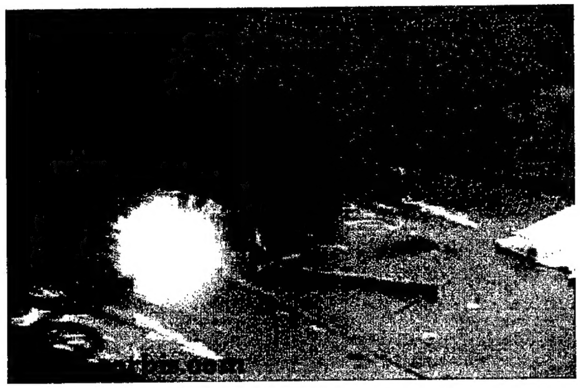
2. Project Objectives

2.1 Description of the Problem

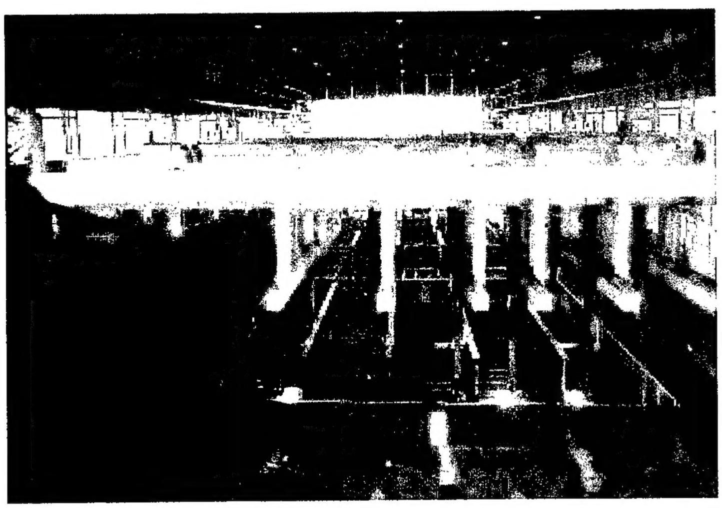
Ship construction represents one of the more challenging planning problems in industry today. An aircraft carrier, for example, is assembled from over 20 million discrete parts. There are an enormous number of alternative ways that a ship can be sequenced and grouped into a hierarchy of assemblies. There is a wide range of costs in these alternatives. An 8 to 1 cost difference between different assembly strategies for building the same end product is not unusual.



The key to reducing construction cost is to move as much work as possible from manual fitting and assembly to process lane based shop fabrication, using automated equipment wherever possible.



Fabricating piping at the assembly platen or onboard ship, for example, typically costs 3 to 8 times as much as the same fabrication in a pipe shop. The purpose of this proposal is to verify the feasibility of developing software tools that reduce ship construction cost by moving more fabrication into shops.



This problem is significant because of the large cost involved. Anticipated savings are $104 million per year in construction costs for U.S. shipyards over a five year period.

2.2 Project Technical Objectives

The technical objectives of this project were to:

- Develop initial system requirements
- Determine the feasibility of developing an automated planning/detailing engine

- Verify that an automated planning/detailing engine could run fast enough to deliver useful results within an acceptable time frame.
- Access the feasibility of developing an engine for automatic pipe routing within pipe banks.
- Estimate the return on investment of deploying an automated planning/detailing engine at different shipyards.

3. Work Performed

3.1 Requirements Definition

System requirements were developed by interviewing key personnel from the following companies:

Alabama Shipbuilding
Bath Iron Works
Dassault Systemes of America
Halter Marine
Global Research and Development Company
Intergraph Corp.
Litton Ingalls Shipbuilding
McDermott Engineering
National Steel and Shipbuilding
Newport News Shipbuilding
Samsung Heavy Industries

3.2 Preliminary Design

A preliminary system design was developed for the planning/detailing engine. The object data model was developed and documented using the Unified Modeling Language. Fast algorithms for generating trial constructions plans have been developed. Algorithms for efficient simulation of pipe bending, automatic pipe welding, and piping surface treatment have been developed.

A two-way interface between the planning/detailing engine and GSCAD (Intergraph's next generation shipbuilding CAD/CAM system) has been designed. A high level design for interfacing the planning/detailing engine to the Dasault Systemes CATIA and DELMIA product lines has been developed.

3.3 Software Prototype

Three software prototypes has been developed which implements the preliminary design for shop fabricated piping. A one-way interface from the GSCAD system has been implemented for feeding data to these prototypes.

3.4 Shipbuilding Return on Investment Study

A return on investment study was performed for the application of automatic planning/detailing engine technology to different ship construction programs. Assuming an annual software license fee of $200,000 for the automatic planning/detailing engine, return on investment is projected to be within less than a month for military ship construction, and two months for commercial ship construction, as summarized below:

Vessel Type	Savings per Vessel	Vessels per Year	Savings per Year	Annual Software License	**Ratio Annual Savings to Annual License**	**Return On Investment (months)**
CVN	$23,500,000	0.14	$3,357,143	$200,000	**16.8**	**0.7**
DD21	$1,600,000	2.00	$3,200,000	$200,000	**16.0**	**0.8**
Tanker	$345,000	3.00	$1,035,000	$200,000	**5.2**	**2.3**

3.5 Automatic Design Detailing of Piping in Banks

One of the most effective ways to move piping fabrication work into the shop is to pre-fabricate entire piping banks. U.S. shipyards currently use this technique, but typically apply it to less than half of the situations where it could be used. The reason for this is lack of good tools for designing piping in banks rather than as individual pipes.

The operation of an automatic pipe bank design tool was envisioned to be as follows:

(1) 3D space is reserved for piping banks using a commercial 3D CAD tool, in a manner similar to reserving space for cableways.
(2) Designers assign pipes to piping banks using a modified version of a commercial cable layout CAD tool. This process will be much faster than laying the piping out in a 3D piping CAD tool.
(3) The cable layout tool passes the pipe bank assignments to the pipe bank layout module developed under in Phase II of this project. This module nests the pipes within each pipe bank and automatically determines a complete 3D geometry for each pipe so that the pipes enter, follow and exit the pipe bank without interfering with each other.
(4) The complete 3D definition of each pipe is passed to commercial 3D piping CAD tool.
(5) Location of pipe joints and build strategy planning is performed automatically as described above.

A high level analysis of the bank piping design problem was performed. This analysis concluded that the same optimization techniques being used in the automatic planning/detailing engine could be applied to automatic pipe bank design detailing.

Beyond the use of similar optimization techniques and CAD system interfaces, however, automatic design of bank piping is a very different problem from automatic planning. For this reason it has been decided to separate this application and not propose it for incorporation in Phase II.

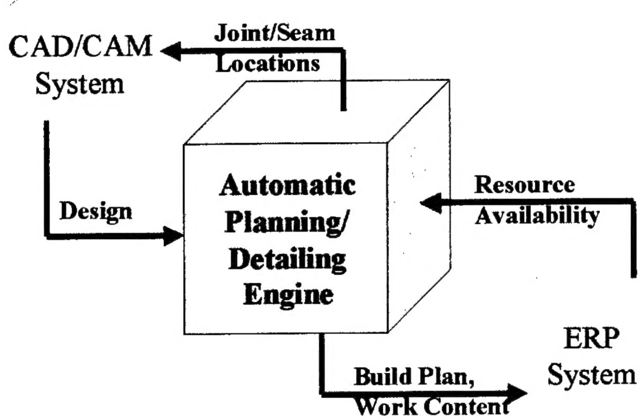
4. Results Obtained

4.1 Requirements

Narrative function points have been found to be the most effective way to collect requirements. Approximately 50 functions points have been identified to date. It is estimated that a production usable automatic planning/detailing engine would need to implement between 200 to 500 function points each for outfitting and structure.

4.2 Preliminary Design

The high-level block diagram for the planning/detailing engine is shown below:



Input to the engine consists of:

3D product model with attributes
High-level schedule
Shipyard facility and process model
Facility availability
Maintainable equipment library

Output from the engine consists of a build plan with:

Assembly hierarchy
Assembly operation/task network
Work center assignments
Work content estimates

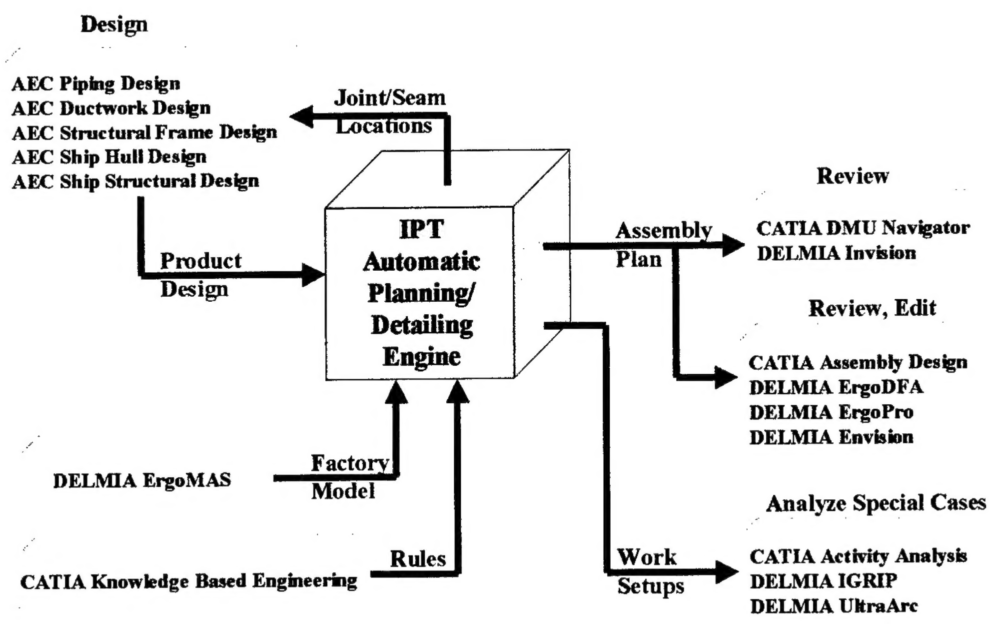
plus the following:

Standard part family/standard process assignments
Locations for structural seams and pipe joints
Equipment maintenance access plan

The high level data model consists of a factory/work center model, a ship design model, a ship generated parts and assembly model, and a task/operation model.

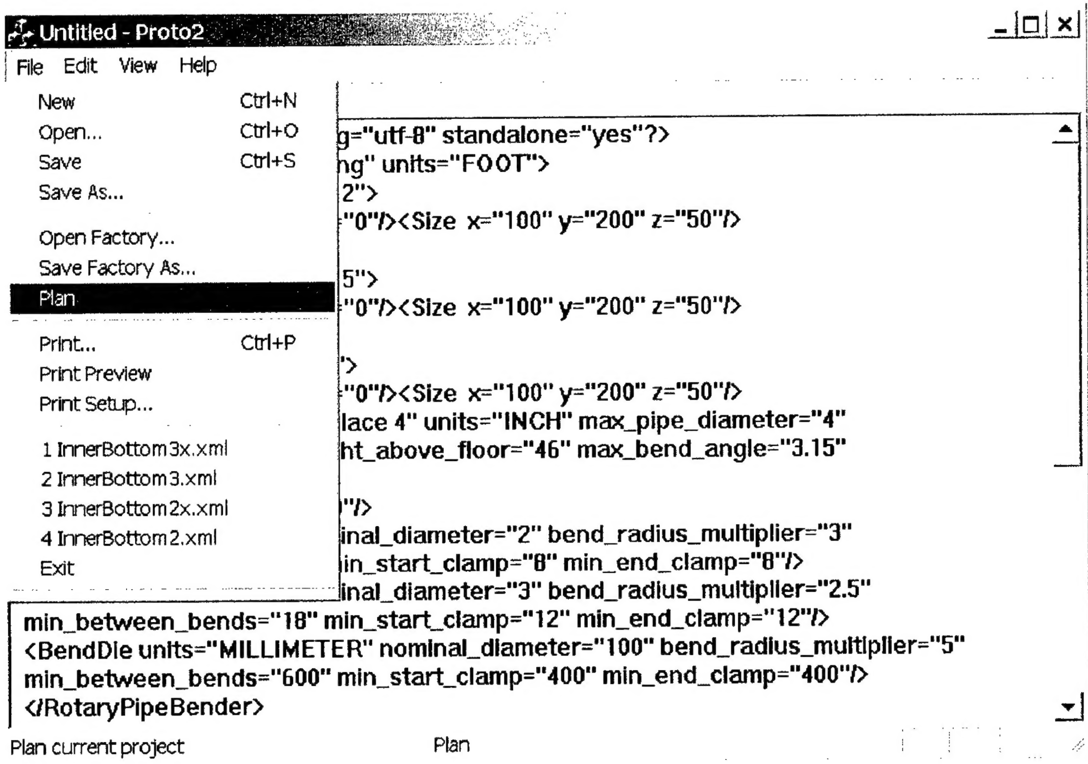
A design for automatic planning of electrical cable pulling and splicing for modular Naval ship construction has been developed. The design makes use of the existing algorithms in the automatic planning/detailing engine and handles the construction and life cycle cost tradeoffs between cable pulling and splicing.

A high level design has been developed for interfacing the planning/detailing engine to the Dassault Systemes CATIA and DELMIA product lines, as shown below:

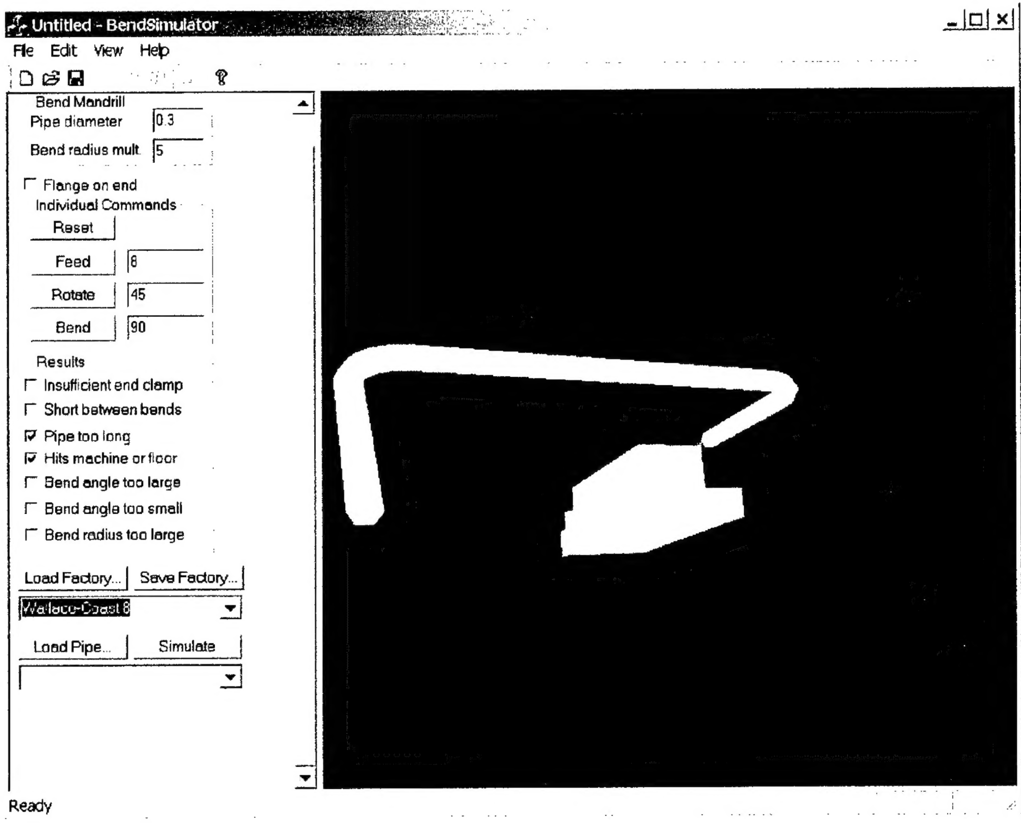


4.3 Software Prototype

Three software prototypes have been constructed. All prototypes use XML files for input and output of data. This allows use of off-the-shelf tools for test data creation and output display. The first two prototypes read design and facility models from XML files and provide a "Plan" command to launch the automatic planning/detailing engine.

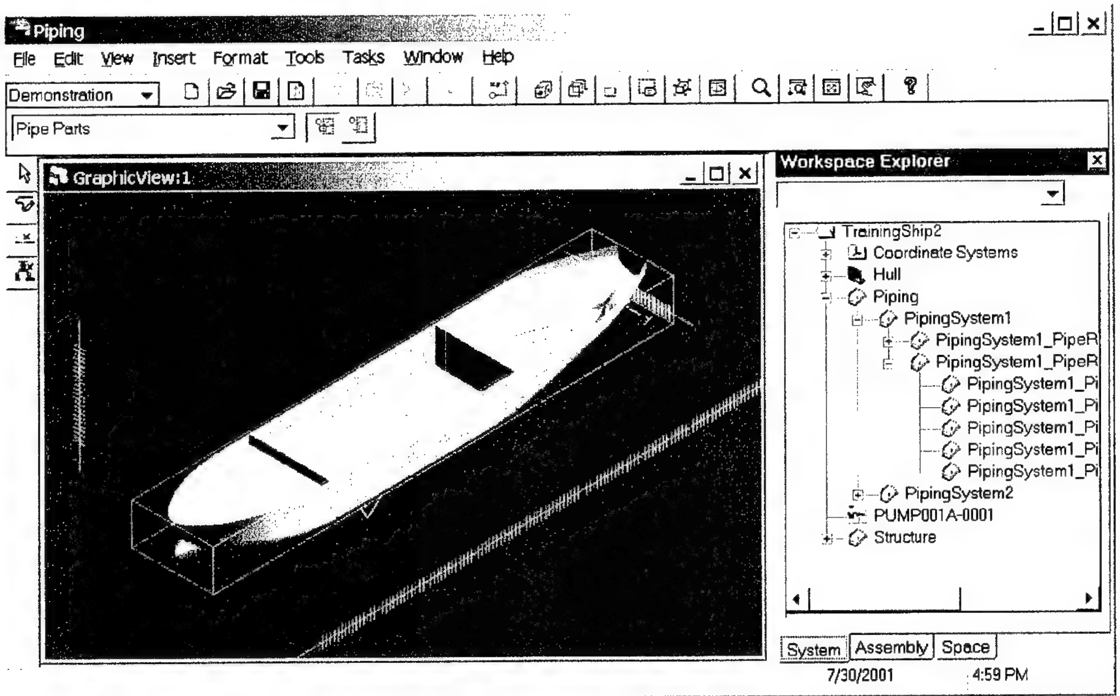


The third prototype is a visual validation tool for the pipe bending simulator.

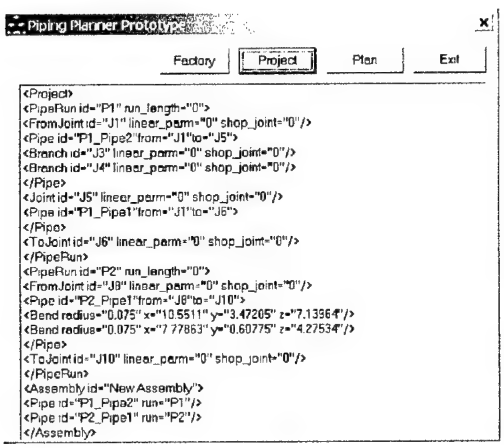


4.4 Interface to GSCAD

The IPT automatic planning/detailing engine prototype has been successfully interfaced to the Intergraph GSCAD ship design package. This interface now provides an excellent source of test data for the engine. A tightly coupled approach is being used in which the IPT software appears to the user as an additional menu command from within the existing GSCAD applications. The screen shot below is a test hull with some piping in GSCAD:



The following screen shot is from the IPT planning/detailing engine prototype test program, after receiving the data from the above test case:



The interface is currently one way, from GSCAD to the IPT engine.

4.5 Shipbuilding Return on Investment Study

Assuming an annual software license fee of $200,000 for the automatic planning/detailing engine, return on investment is projected to be within less than a month for military ship construction, and two months for commercial ship construction, as summarized below:

Vessel Type	Savings per Vessel	Vessels per Year	Savings per Year	Annual Software License	**Ratio Annual Savings to Annual License**	**Return On Investment (months)**
CVN	$32,300,000	0.14	$4,614,286	$200,000	**23.1**	**0.5**
DD21	$2,300,000	2.00	$4,600,000	$200,000	**23.0**	**0.5**
Tanker	$531,667	3.00	$1,595,000	$200,000	**8.0**	**1.5**

Savings projections assumptions for aircraft carrier construction are given below. Key assumptions are that 6% of structural work and 12% of piping work is moved from field fabrication to shop fabrication through optimal planning, and that shop fabrication is 3 times as efficient as field fabrication.

		%	$	mh	**Savings $**
Labor Rate			$35		
Vessel Type	CVN				
Construction Cost			$2,000,000,000		
Material Cost		70%	$1,400,000,000		
Labor Cost		30%	$600,000,000	17,142,857	
Planning labor (before)		1%	$7,000,000	200,000	
Structural fab labor (before)		50%	$300,000,000	8,571,429	
Piping fab labor (before)		35%	$210,000,000	6,000,000	
Other labor			$83,000,000		
Shop labor as a % of total (before)					
Structure		85%		7,285,714	
Piping		50%		3,000,000	
Field labor as a % of total (before)					
Structure		15%		1,285,714	
Piping		50%		3,000,000	
Planning labor reduction		50%			
Labor moved from field to shop through optimal planning					
Structure		6%			
Piping		12%			
Ratio field to shop labor for same tasks					
Structure	3.00				
Piping	3.00				
Planning labor (after)			$3,500,000	3,000,000	**$3,500,000**
Structural fab labor (after)			$288,000,000	8,228,571	**$12,000,000**
Piping fab labor (after)			$193,200,000	5,520,000	**$16,800,000**
Construction Cost (after)			$1,967,700,000		**$32,300,000**

Vessels built/year	0.14		**$4,614,286**

Savings projections assumptions for DD21 class vessel construction are given below:

		%	$	mh	Savings $
Labor Rate			$35		
Vessel Type	DD21				
Construction Cost			$200,000,000		
Material Cost		70%	$140,000,000		
Labor Cost		30%	$60,000,000	1,714,286	
Planning labor (before)		2%	$1,400,000	40,000	
Structural fab labor (before)		50%	$30,000,000	857,143	
Piping fab labor (before)		25%	$15,000,000	428,571	
Other labor			$13,600,000		
Shop labor as a % of total (before)					
Structure		85%		728,571	
Piping		70%		300,000	
Field labor as a % of total (before)					
Structure		15%		128,571	
Piping		30%		128,571	
Planning labor reduction		50%			
Labor moved from field to shop through optimal planning					
Structure		4%			
Piping		8%			
Ratio field to shop labor for same tasks					
Structure	3.00				
Piping	3.00				
Planning labor (after)			$700,000	214,286	**$700,000**
Structural fab labor (after)			$29,200,000	834,286	**$800,000**
Piping fab labor (after)			$14,200,000	405,714	**$800,000**
Construction Cost (after)			$197,700,000		**$2,300,000**
Vessels built/year	2.00				**$4,600,000**

Savings projections assumptions for commercial tanker construction are given below:

		%	$	mh	Savings $
Labor Rate			$35		
Vessel Type	tanker				
Construction Cost			$40,000,000		
Material Cost		60%	$24,000,000		
Labor Cost		40%	$16,000,000	457,143	
Planning labor (before)		1%	$210,000	6,000	
Structural fab labor (before)		50%	$8,000,000	228,571	
Piping fab labor (before)		25%	$4,000,000	114,286	
Other labor			$3,790,000		
Shop labor as a % of total (before)					
Structure		85%		194,286	
Piping		70%		80,000	
Field labor as a % of total (before)					
Structure		15%		34,286	
Piping		30%		34,286	
Planning labor reduction		50%			
Labor moved from field to shop through optimal planning					
Structure		4%			
Piping		8%			
Ratio field to shop labor for same tasks					
Structure	3.00				
Piping	3.00				
Planning labor (after)			$105,000	57,143	**$105,000**
Structural fab labor (after)			$7,786,667	222,476	**$213,333**
Piping fab labor (after)			$3,786,667	108,190	**$213,333**
Construction Cost (after)			$39,468,333		**$531,667**
Vessels built/year	3.00				**$1,595,000**

4.6 Automatic Design Detailing of Piping in Banks

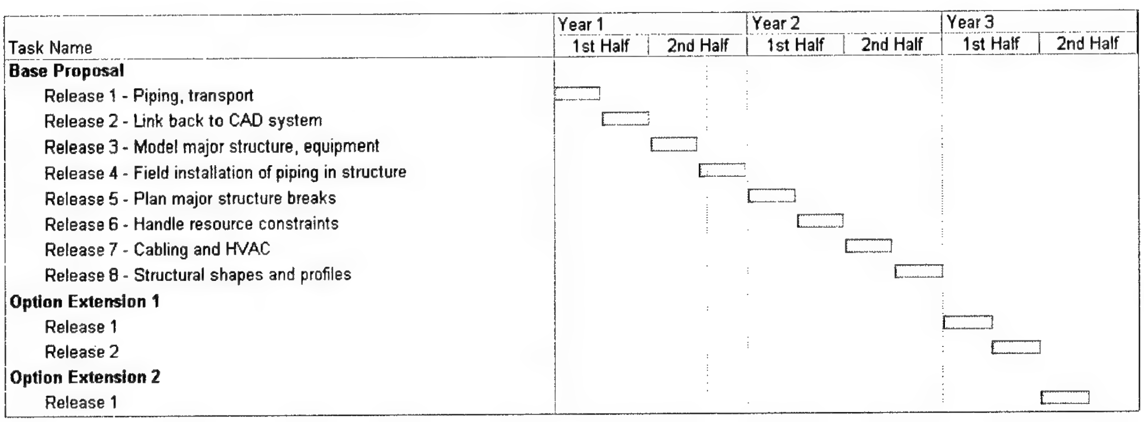
One of the most effective ways to move piping fabrication work into the shop is to pre-fabricate entire piping banks. U.S. shipyards currently use this technique, but typically apply it to less than half of the situations where it could be used. The reason for this is lack of good tools for designing piping in banks rather than as individual pipes.

A high level analysis of the bank piping design problem was performed. This analysis concluded that the same optimization techniques being used in the automatic planning/detailing engine could be applied to automatic pipe bank design detailing.

Beyond the use of similar optimization techniques and CAD system interfaces, however, automatic design of bank piping is a very different problem from automatic planning. For this reason it has been decided to separate this application and not propose it for incorporation in Phase II.

4.7 Overview of Work Plan for Phase II

The Phase II work plan is to grow the successful Phase I "proof of concept" prototype into a "production worthy" system for use in shipbuilding. The "Agile Programming" methodology will be used for software development, with frequent releases and incremental addition of functionality to the system. The major activities and timeline for the project are shown in the Gantt chart below. The Gantt chart covers the 2-year base proposal, plus a 6-month optional extension #1, and a 3-month optional extension #2.



4.7.1 Base Proposal

The base proposal focuses on developing and testing functionality in the core planning/detailing engine. The plan is to first develop a solid demonstration of automatic planning and detailing for piping, then add the ability to plan major structure breaks, then other outfitting, and finally planning of detail structure. GSCAD (Intergraph's next generation ship design system) will be used as the main test bed for exercising and testing the planning/detailing engine.

The work plan is broken into eight releases, each representing additional capability added to a functioning, demonstratable system. The work tasks for each of the eight releases are described in more detail in the Phase II proposal.

4.7.2 Methodology

The "Agile Programming" software methodology will be used on this project. This methodology is based on a "successive refinement" approach where a working prototype is evolved into a production worthy system. A key aspect of this methodology is frequent, early testing and rapid evolution to a functionality limited, but stable system. Functionality is then added to the system with each release.

The priorities for adding functionality to releases will depend heavily on input from shipyards. The basic plan is to expand the automatic planning/detailing capability for piping developed in Phase I, deal with installation of piping in manually planned structural units. This will be followed by automatic planning/detailing of major ship structure. After that cabling and HVAC planning will be added. This sequencing of functionality is subject to change, based on input from shipyards and availability of functionality from CAD systems.

Releases are scheduled every three months. For each release, there are several repeatable tasks:

Define Requirements
Interview shipyard personnel. Write functional description of requirements. Make sketches or get pictures.

Select Features
Select requirements for incorporation in the release, based on importance to shipyards and work required.

Design Software
Update and revise the object data model. Update and revise data mappings for interfaces to external systems. Develop new algorithms, if required. Define code transformations required from the existing code base. Consider various alternative designs for functionality that are capable of meeting the specifications.

Develop Test Harness
Update and revise the test case data files, scripts, and documentation to reflect the new requirements. Insure that each functional requirement is tested. Update automated test scripts as required.

Code Software
Implement the design in C++ and debug using the test harness. The object of this task is to write the needed code to successfully perform the requirements.

System Test Software
Exercise the overall system using test scripts. Verify that prior functionality has not been lost and that new requirements are met. The automated planning system engine will be functionally tested to see if its components meet the design specifications.

Write User Documentation
Update the user documentation for the system. Also update the PowerPoint overview of the system to reflect new functionality.

Demonstrate to Shipyards
Demonstrate the revised system to shipyard personnel. This is intended to gather feedback that starts the requirements gathering for the next release.

4.7.3 Software Development Management

The Principal Investigator for this project, Dr. Patrick Rourke, has 20+ years experience in managing technical software development teams of up to 18 people.

5. Estimate of Technical Feasibility

The feasibility of developing an automatic planning/detailing engine has been validated. The test prototype generates a detailed product model and construction plan in under thirty seconds for a test case consisting of six pipe lines. Solution times are roughly linear with the size of the problem, so applying the test engine to all the outfitting in a construction block should yield answers in less than 15 minutes, which is an acceptable time delay.

The feasibility of interfacing an automatic planning/detailing engine to a CAD/CAM system has been demonstrated. In addition to interfacing the prototype planning/detailing engine to GSCAD, some of the simulation components of the engine have now been incorporated in the GSCAD production software.

6. Potential Applications

The automated planning/detailing engine will find wide use in shipbuilding for construction planning, design detailing, and maintenance planning. The software could also have significant application for commercial industrial building and for the power and processing plant construction planning.

Prerequisite to the application of this technology include the use of intelligent 3D CAD models for design and deployment of an integrated manufacturing and assembly operation. The shipbuilding industry is at this point now. Shipbuilders recognize immediately the benefits of this technology. Parts of the plant design and commercial construction industry are approaching this point. Modern plant construction typically involves off-site fabrication of assemblies, which are then trucked to the commercial construction site. The automatic planning/detailing engine is directly applicable to these entities, as it is aimed at optimizing the design and plan for these factors.

The largest market potential is in commercial building construction. The use of intelligent 3D CAD technology for building design is growing, but is not yet widespread, however.

The worldwide market potential is estimated at $3.6 million revenue per year in shipbuilding. This assumes that 40% of the 30 major shipyards become customers, at an annual software lease of $200,000, and that 20% of the 120 medium sized yards are customers at an annual lease of $50,000. The size of the potential market in the process and power plant industry is estimated at $5 million per year. The market potential in building construction is substantially larger, perhaps $100 million per year, but is

dependent on widespread adoption of 3D modeling techniques. That adoption will take somewhere between 3 to 10 years.

The technology developed here can also be helpful to customers who are in the process of switching to a modern ERP system. Many customers are being market and competitively driven to replace antiquated ERP systems. The automatic planning/detailing engine will reduce substantially the impact of switching to a modern ERP system, such as SAP. The automatic planning engine generates most of the required data automatically, thereby drastically reducing the costs of initiating SAP.

The same technology that can plan ship assembly can be applied to planning disassembly and removal for maintenance. Planning maintenance access and removal paths for equipment is a time-consuming task, and is typically only done for larger items. More importantly, with present design tools it is difficult to make design trade-offs that minimize the total ship life cycle cost.

The benefits of automated life cycle planning are:

- Life cycle cost is considered up-front rather than at the tail end of the design process,
- Maintainability analysis is applied to all repairable/replaceable items, not just the major ones.
- Design trade-off decisions are made using a ship life cycle mission model rather than just minimizing ship construction costs.

Anticipated life cycle savings are $16 million per year, which assumes a 5% reduction in ship maintenance cost through optimum design for maintainability. Compounding this saving over the life of each ship, and applying discounted cash flow, would increase the true value of this savings by an order of magnitude.

Input from shipyards indicates that there is substantial interest in spin-off modules of the engine as stand-alone products. Potential products include manufacturing simulators as design checks for CAD systems, and an automatic planning engine that does not perform design detailing, but does generate an optimal plan from a manually detailed design.

7. Commitment to a Phase II Proposal

Industrial Planning Technology Inc. is committed to developing commercial software products based on this technology and marketing to the shipbuilding, process plant, and building construction industries.

The fact that Industrial Planning Technology has secured both outside equity investment and an advance purchase order for the technology is ample evidence of the commercial viability of the proposed product.

Industrial Planning Technology has made a strong commitment to a successful commercialization Phase II (and Phase III) of its automated planning system. In addition, several commercially viable, modular spin-off products have been identified. The potential for commercial (Government and private sector) application and the benefits expected to accrue from this commercialization are demonstrated by the successful acquisition of a commitment for outside investment funding, during both Phase II and Phase III.

The qualifications of the proposed principal investigator and supporting staff include not only the ability to perform the research and development, but also the ability to successfully commercialize the results. The principal investigator is confident that automated planning, based on the proposed automated construction planning system, will be important elements in future shipbuilding planning systems.

The technical personnel at IPT form an innovative team with broad scientific and engineering backgrounds. The interchange of ideas necessary for problem solving occurs frequently and spontaneously. The personnel for this project are well suited to develop the new automated planning system using the newly developed algorithms and to solve technical problems that may arise during Phase II of the project.

The IPT team also has successful experience in the founding and running of new technology start-ups, with sales and marketing background including a successful track record of launching technology into worldwide marketable products. This expertise will be used to aid in the commercialization of the new automated planning technology and in integration with shipyards' existing CAD and ERP systems.

At the completion of Phase II, the technologies will be readied into a production worthy system for transfer to the commercial market. It is also envisioned that several plug-in spin-offs will be made available as independent modules. These modules would be well specified and function for specific shipyards. The system would be made available for integration by other commercial entities and for integration into CAD and ERP products.